Program Analysis – Lecture 13
Analyzing Concurrent Programs
(Part 1)

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Warm-up Quiz

What does the following code print?

```
function d(x) {
    return new Promise(resolve => {
        setTimeout(() => {
            resolve(x * 2);
        }, 2000);
    });
  }

d(5).then((r) => {
    console.log(r);
});
```

5 **10** **undefined** **Something else**

https://ilias3.uni-stuttgart.de/vote/KN2I

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  }

d(5).then((r) => {
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});
```

(but only after waiting for two seconds)

5 | **10** | undefined | Something else

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Warm-up Quiz

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});
```

Promise: Represents a result that is not yet complete

5 | **10** | **undefined** | **Something else**

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Warm-up Quiz

What does the following code print?

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        setTimeout(() => {
            resolve(x * 2);
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    });
  }

d(5).then((r) => {
    console.log(r);
});
```

Wait 2,000 milliseconds and then return the promise's result

5 **10** **undefined** **Something else**

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Warm-up Quiz

What does the following code print?

```
function d(x) {
    return new Promise(resolve => {
        setTimeout(() => {
            resolve(x * 2);
        }, 2000);
    });
  }

d(5).then((r) => {
    console.log(r);
});
```

Wait for the promise to resolve and then use its result

5 **10** **undefined** **Something else**

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Outline

1. **Introduction**
2. **Dynamic Data Race Detection**
3. **Testing Thread-Safe Classes**

Mostly based on these papers:

- *Eraser: A Dynamic Data Race Detector for Multithreaded Programs*, Savage et al., ACM TOCS, 1997
- *Fully Automatic and Precise Detection of Thread Safety Violations*, Pradel and Gross, PLDI 2012

Why Bother with Concurrency?

- The free lunch provided by Moore's law is over
  - CPU clock speeds stopped to increase around 2005
  - Instead, multi-core processors became mainstream
  - Need concurrent programs to make full use of the hardware
- Many real-world problems are inherently concurrent, e.g.,
  - Servers must handle multiple concurrent requests
  - Computations done on huge data often are "embarrasingly parallel"

Why Bother with Concurrency?

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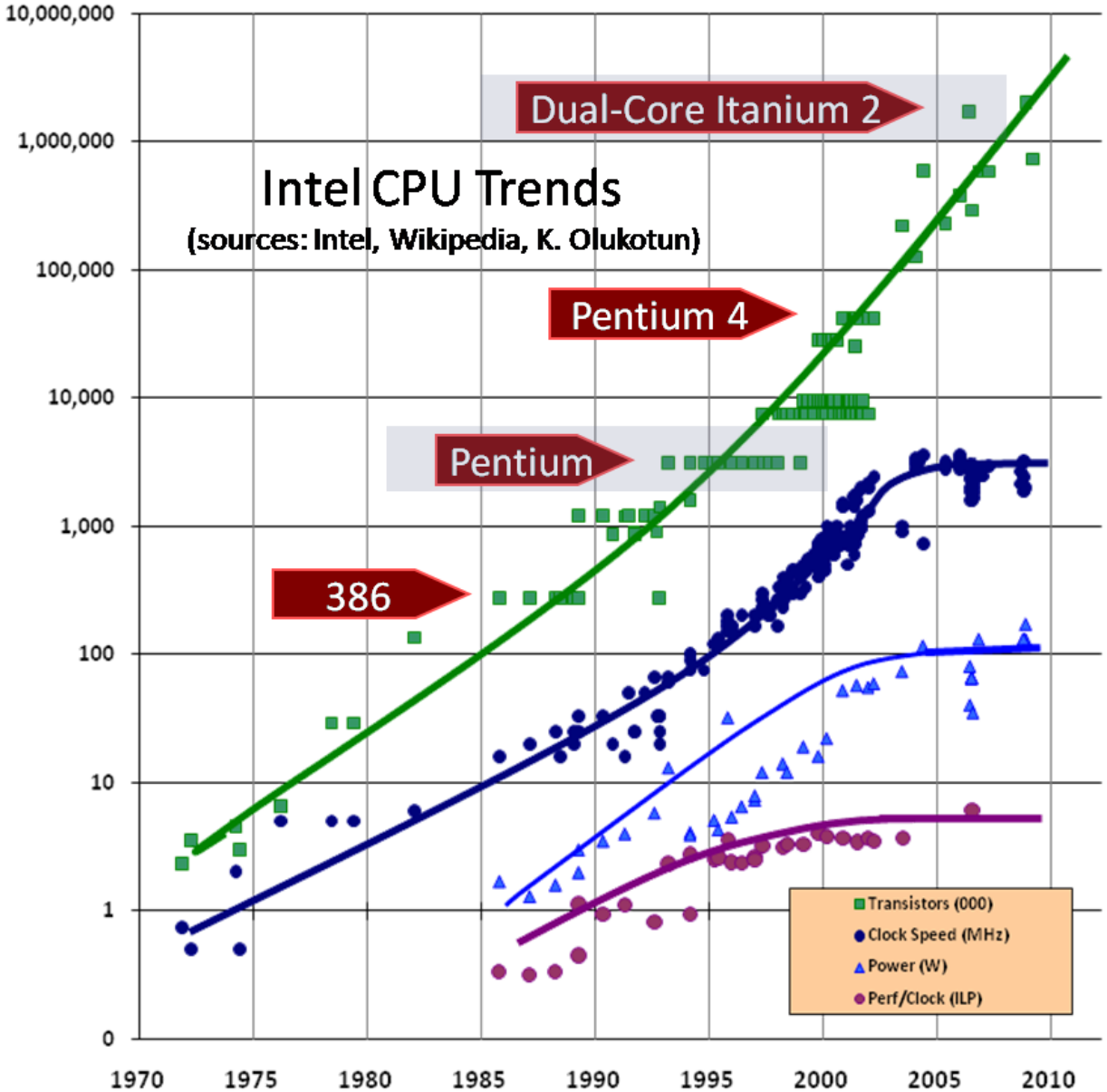

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  - Servers must handle multiple concurrent requests
  - Computations done on huge data often are "embarrasingly parallel"

Concurrency Styles

- Message-passing
  - Popular for large-scale scientific computing, e.g., MPI (message-passing interface)
  - Used in actor concurrency model, e.g., popular in Erlang and Scala
  - No shared memory (ideally), all communication via messages
- Thread-based, shared memory
  - Multiple concurrently executing threads
  - All threads access the same shared memory
  - Synchronize via locks and barriers

Concurrency Styles

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Focus of this lecture

- Thread-based, shared memory
  - Multiple concurrently executing threads
  - All threads access the same shared memory
  - Synchronize via locks and barriers

Example

```
int a = 0, b = 0;
boolean r = false, t = false;
```


```
a = 1;                    t = r;
r = true;                 b = a;
```

What does this program mean?

$\rightarrow$ Behavior depends on thread interleaving

$a = b = 0 \; ; \quad r = t = \text{false}$

$a = 1$
$r = \text{true}$

$t = r$
$b = a$

1	2	3	4	5	6
$a = 1$	$a = 1$	$a = 1$	$t = r$	$t = r$	$t = r$
$r = \text{true}$	$t = r$	$t = r$	$b = a$	$a = 1$	$a = 1$
$t = r$	$b = a$	$r = \text{true}$	$a = 1$	$r = \text{true}$	$b = a$
$b = a$	$r = \text{true}$	$b = a$	$r = \text{true}$	$b = a$	$r = \text{true}$
$t = \text{true}$	$t = \text{false}$	$t = \text{false}$	$t = \text{false}$	$t = \text{false}$	$t = \text{false}$
$b = 1$	$b = 1$	$b = 1$	$b = 0$	$b = 1$	$b = 1$

$t = \text{true}$ implies $b = 1$

Sequential Consistency

Assumption made here:

Programs execute under sequential consistency

- Program order is preserved: Each thread's instructions execute in the specified order
- Shared memory behaves like a global array: Reads and writes are done immediately

- We assume sequential consistency for the rest of the lecture
- Many real-world platforms have more complex semantics ("memory models")

What Can Go Wrong?

Common source of errors: Data races

- Two accesses to the same shared memory location
- At least one access is a write
- Ordering of accesses is non-deterministic

Example

```
// bank account
int balance = 10;
```

Thread 1 Thread 2

```
// deposit money
int tmp1 = balance;
balance = tmp1 + 5;
```

```
// withdraw money
int tmp2 = balance;
balance = tmp2 - 7;
```

Example

```
// bank account
int balance = 10;
```

Shared memory location

Thread 1 | Thread 2

```
// deposit money
int tmp1 = balance;
balance = tmp1 + 5;
```

```
// withdraw money
int tmp2 = balance;
balance = tmp2 - 7;
```

Read

Write

Example

```
// bank account
int balance = 10;
```

Thread 1 Thread 2

```
// deposit money
int tmp1 = balance;
balance = tmp1 + 5;
```

```
// withdraw money
int tmp2 = balance;
balance = tmp2 - 7;
```

3 races

Example

```
// bank account
int balance = 10;
```

Thread 1 | Thread 2

```
// deposit money
int tmp1 = balance;
balance = tmp1 + 5;
```

```
// withdraw money
int tmp2 = balance;
balance = tmp2 - 7;
```

Quiz: What values can `balance` have after executing this code?

https://ilias3.uni-stuttgart.de/vote/KN2I

Example

```
// bank account
int balance = 10;
```

Thread 1 | Thread 2

```
// deposit money
int tmp1 = balance;
balance = tmp1 + 5;
```

```
// withdraw money
int tmp2 = balance;
balance = tmp2 - 7;
```

Possible outcomes:

`balance` may be 3, 8, and 15

But: Only 8 is correct

Avoiding Data Races

Use locks to ensure that accesses to shared memory do not interfere

```
int balance = 10;
```

Thread 1

```
acquire(L);
int tmp1 = balance;
balance = tmp1 + 5;
release(L);
```

Thread 2

```
acquire(L);
int tmp2 = balance;
balance = tmp2 - 7;
release(L);
```

Avoiding Data Races

Use locks to ensure that accesses to shared memory do not interfere

```
int balance = 10;
```

Thread 1

```
acquire(L);
int tmp1 = balance;
balance = tmp1 + 5;
release(L);
```

Thread 2

```
acquire(L);
int tmp2 = balance;
balance = tmp2 - 7;
release(L);
```

Same lock ⇒ Mutually exclusive critical sections

Avoiding Data Races

Use locks to ensure that accesses to shared memory do not interfere

```
int balance = 10;
```

Thread 1

```
synchronized (L) {
  int tmp1 = balance;
  balance = tmp1 + 5;
}
```

Thread 2

```
synchronized (L) {
  int tmp2 = balance;
  balance = tmp2 - 7;
}
```

(Java syntax)

Outline

1. **Introduction**
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Eraser: Data Race Detection

- Basic idea: Look for ”unprotected” accesses to shared memory
- Assumption: All accesses to a shared memory location v should happen while holding the same lock L
  $\rightarrow$ Consistent locking discipline
- Dynamic analysis that monitors all lock acquisitions, lock releases, and accesses of shared memory locations

Lockset Algorithm (Simple Form)

- **Let $locksHeld(t)$ be the set of locks held by thread t**
- **For each shared memory location v, initialize $C(v)$ to the set of all locks**
- **On each access to v by thread t**
  - Set $C(v) := C(v) \cap locksHeld(t)$
  - If $C(v) = \emptyset$, issue a warning

Lockset Algorithm (Simple Form)

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  - If $C(v) = \emptyset$, issue a warning

Lockset

Lockset refinement

balance = 10

```
acquire (L1)
    tmp1 = balance
    balance = tmp1 + a
release (L1)
```

```
tmp2 = balance
acquire (L2)
    balance = tmp2 - b
release (L2)
```

Instruction	locksHeld	C(balance)
balance = 10	{}	{L1, L2}
acquire (L1)	{L1}	{L1, L2}
tmp1 = balance	{L1}	{L1}
balance = tmp1 + a	{L1}	{L1}
release (L1)	{}	{L1}
tmp2 = balance	{}	{} → warning: data race
acquire (L2)	{L2}	{}
balance = tmp2 - b	{L2}	{}
release (L2)	{}	{}

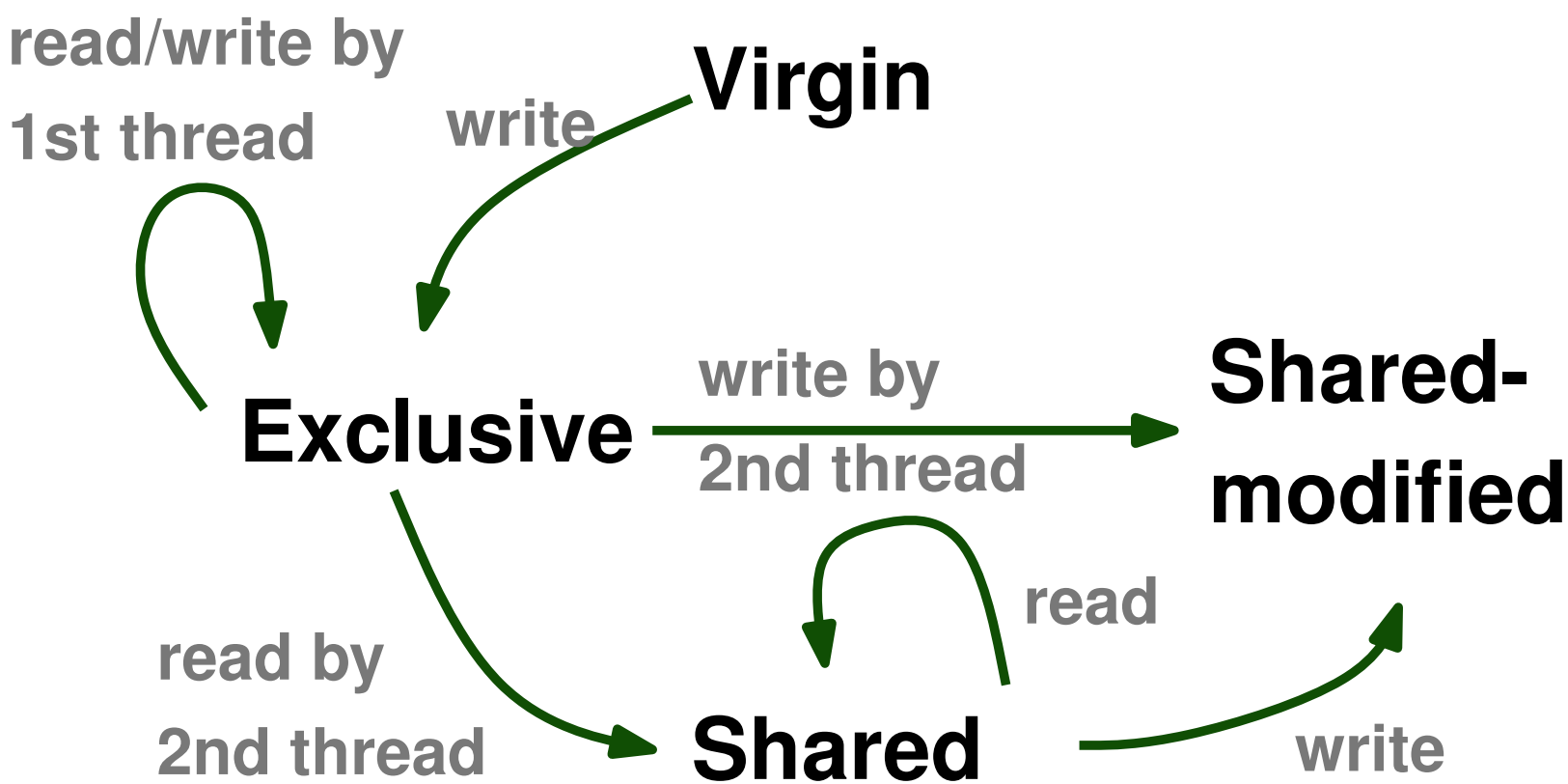
Simple Lockset is Too Strict

Simple lockset algorithm produces false positives for

- variables initialized without locks held
- read-shared data read without locks held
- read-write locking mechanisms (producer-consumer style)

Refining the Lockset Algorithm

- Keep state of each shared memory location
- Issue warnings only in the Shared-modified state



Summary: Eraser

- **Dynamic analysis to detect data races**
- **Assumes consistent locking discipline**
- **Limitations**
  - May report false positives when locks are acquired inconsistently but correctly
  - May miss data races because it does not consider all possible interleavings

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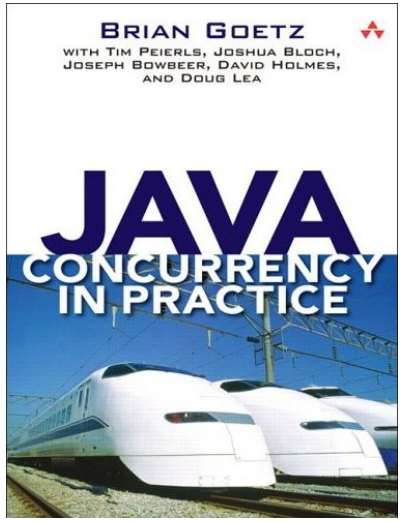
Thread Safety

- Popular way to encapsulate the challenges of concurrent programming: Thread-safe classes
- Class ensures correct synchronization
- Clients can use instances as if they were alone
- Rest of program can treat implementation of thread-safe class as a blackbox

Thread Safety (2)

“behaves correctly when accessed from multiple threads ... with no additional synchronization ... (in the) calling code”

page 18



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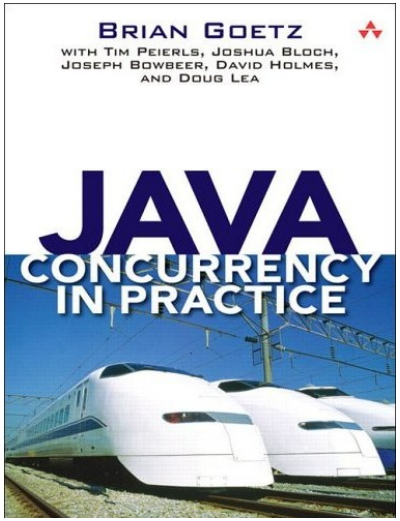

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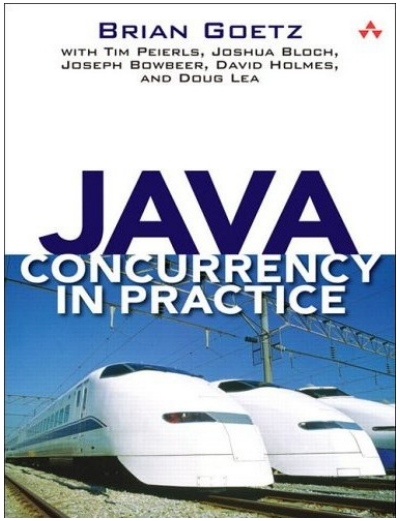

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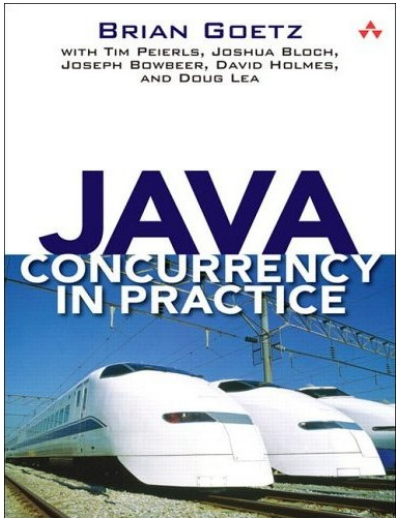

"operations ... behave as if they occur in some serial order that is consistent with the order of the method calls made by each of the individual threads"

StringBuffer API documentation, JDK 6

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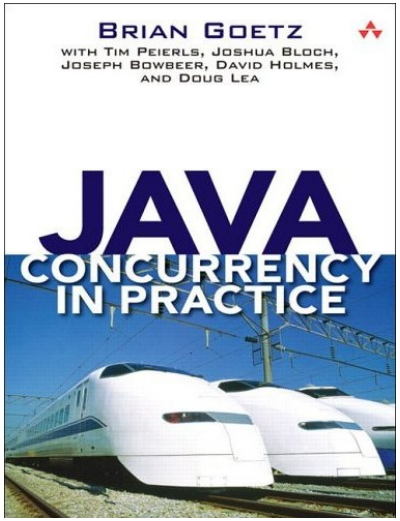

"operations ... behave as if they occur in some serial order that is consistent with the order of the method calls made by each of the individual threads"

StringBuffer API documentation, JDK 6

Example from JDK

```
StringBuffer b = new StringBuffer()
```


```
b.append("a")        b.append("c")
b.append("b")
```

Example from JDK

```
StringBuffer b = new StringBuffer()
```


```
b.append("a")
b.append("b")
```

```
b.append("c")
```

Quiz: What can be the content of `b` if `StringBuffer` is thread-safe?

Example from JDK

```
StringBuffer b = new StringBuffer()
```


```
b.append("a")          b.append("c")
b.append("b")
```

"abc" ✓ "cab" ✓ "acb" ✓ "ac" ✗ "bac" ✗

Example from JDK

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StringBuffer b = new StringBuffer()
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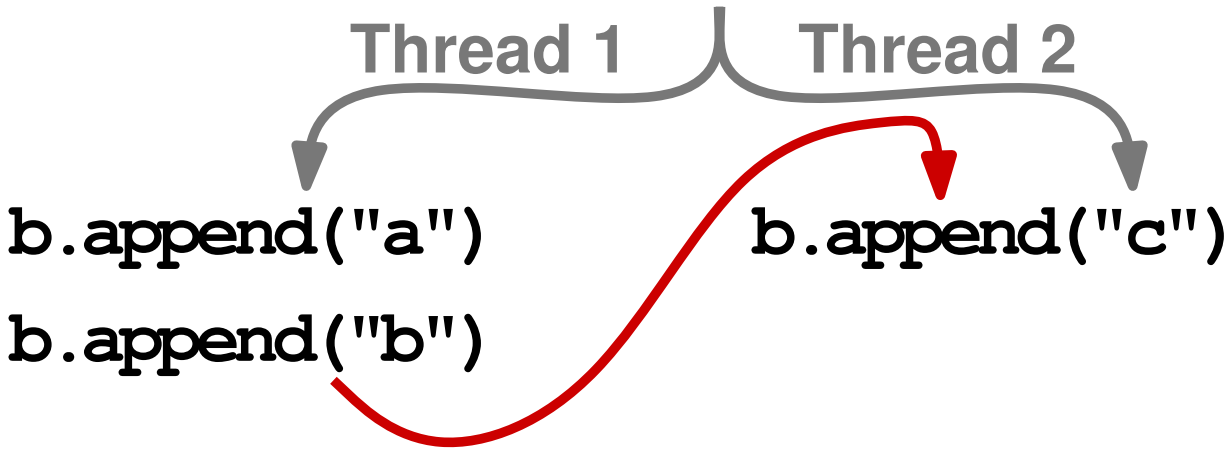

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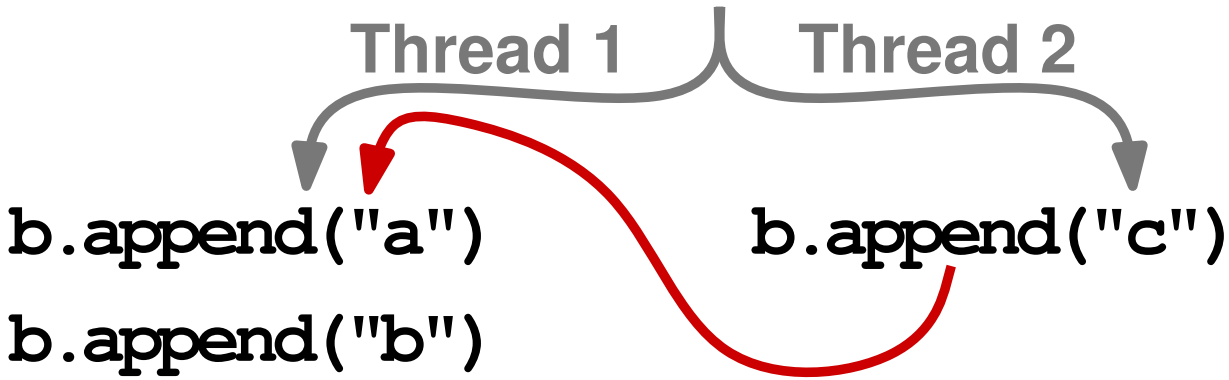

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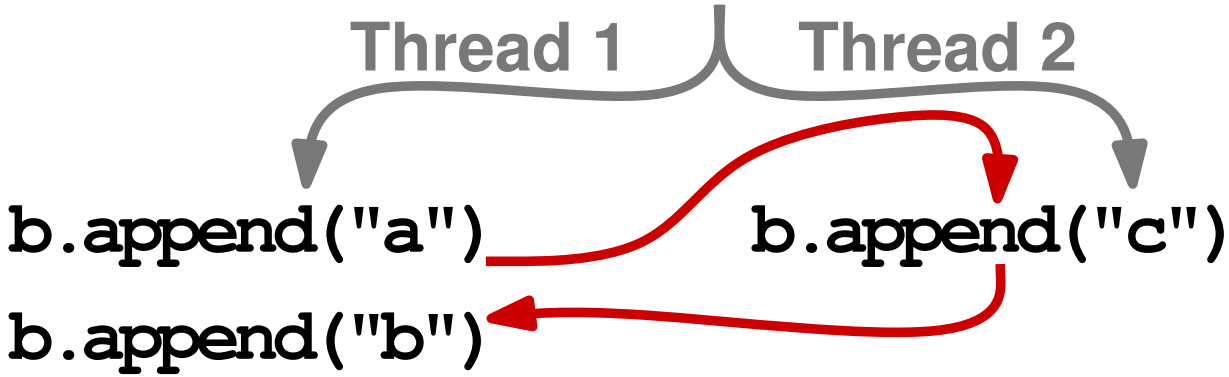

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Example from JDK

```
StringBuffer b = new StringBuffer()
```

Thread 1 | Thread 2

```
b.append("a")        b.append("c")
b.append("b")
```

"abc" ✓ "cab" ✓ "acb" ✓ "ac" ✗ "bac" ✗

Testing Thread-Safe Classes

- Correctness of program relies on thread safety of specific classes
- But: What if the class is actually not thread-safe?

- ConTeGe = Concurrent Test Generator
- Creates multi-threaded unit tests
- Detects thread safety violations by comparing concurrent behavior against linearizations

Example Bug from JDK

```
StringBuffer b = new StringBuffer()
b.append("abc")
```


```
b.insert(1, b)        b.deleteCharAt(1)
```

Example Bug from JDK

```
StringBuffer b = new StringBuffer()
b.append("abc")
```

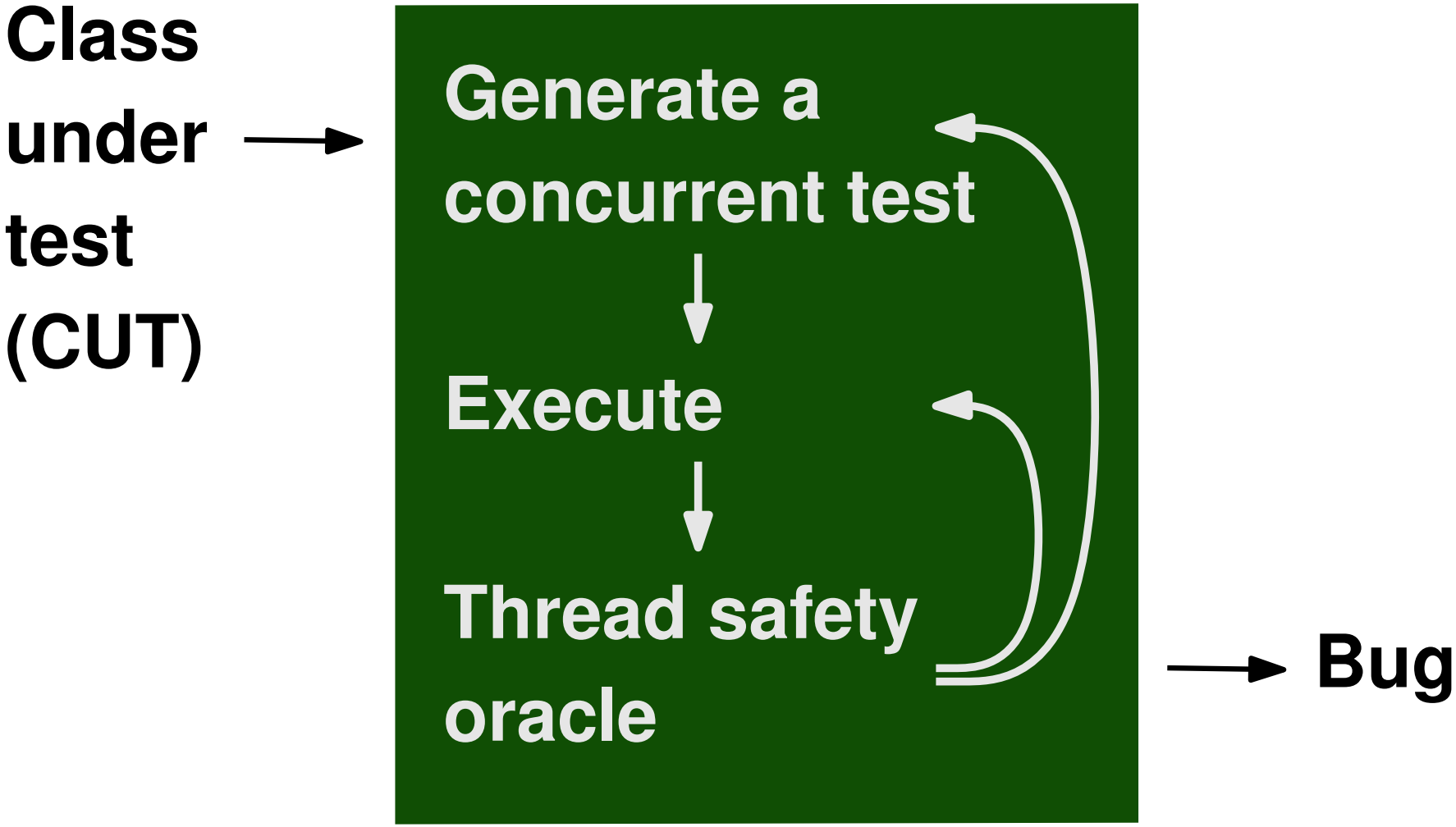
Thread 1 Thread 2

```
b.insert(1, b)        b.deleteCharAt(1)
```

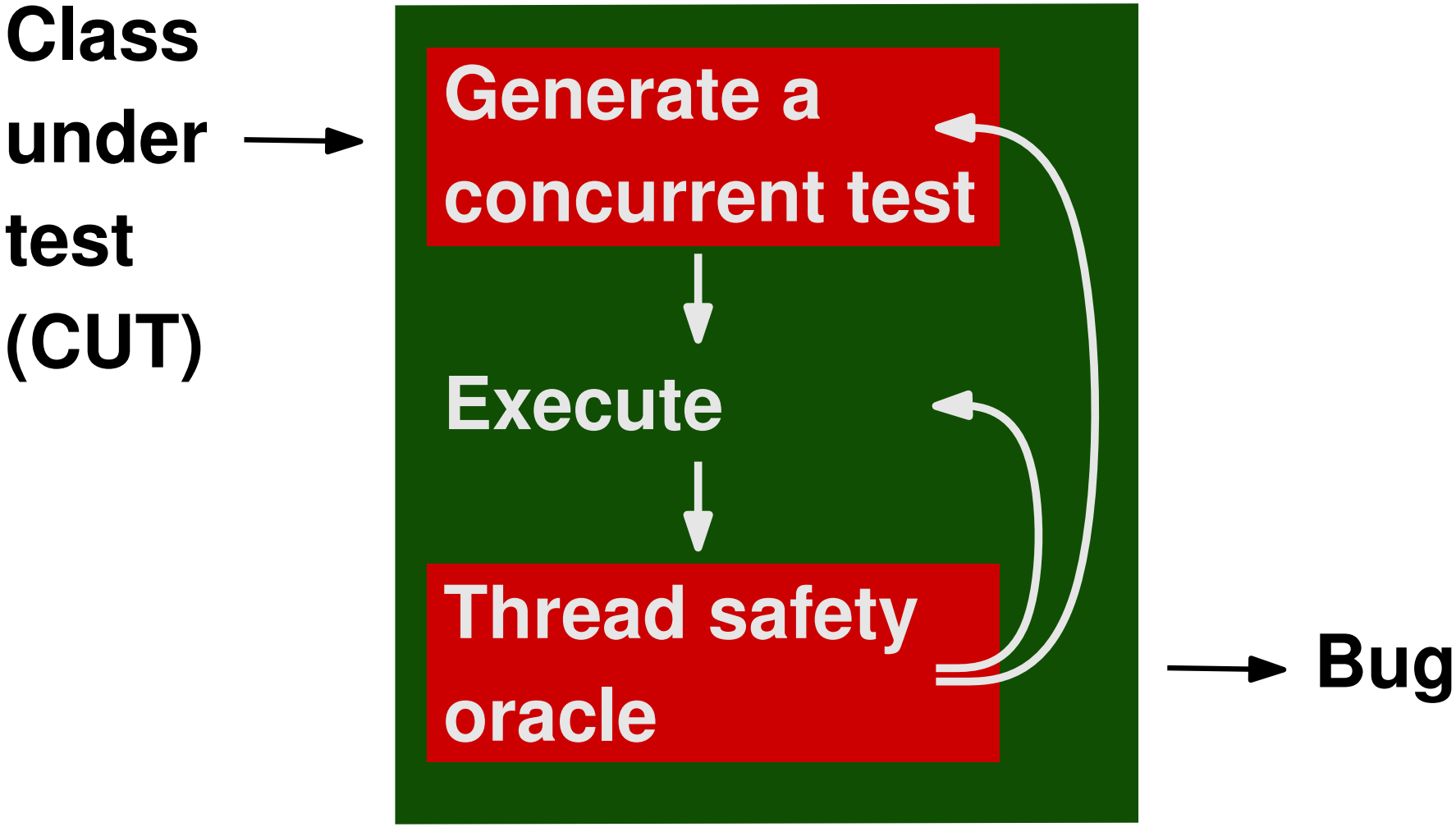
IndexOutOfBoundsException

Confirmed as bug: Issue #7100996

ConTeGe


Class under test (CUT)
Generate a concurrent test
Execute
Thread safety oracle
Bug

ConTeGe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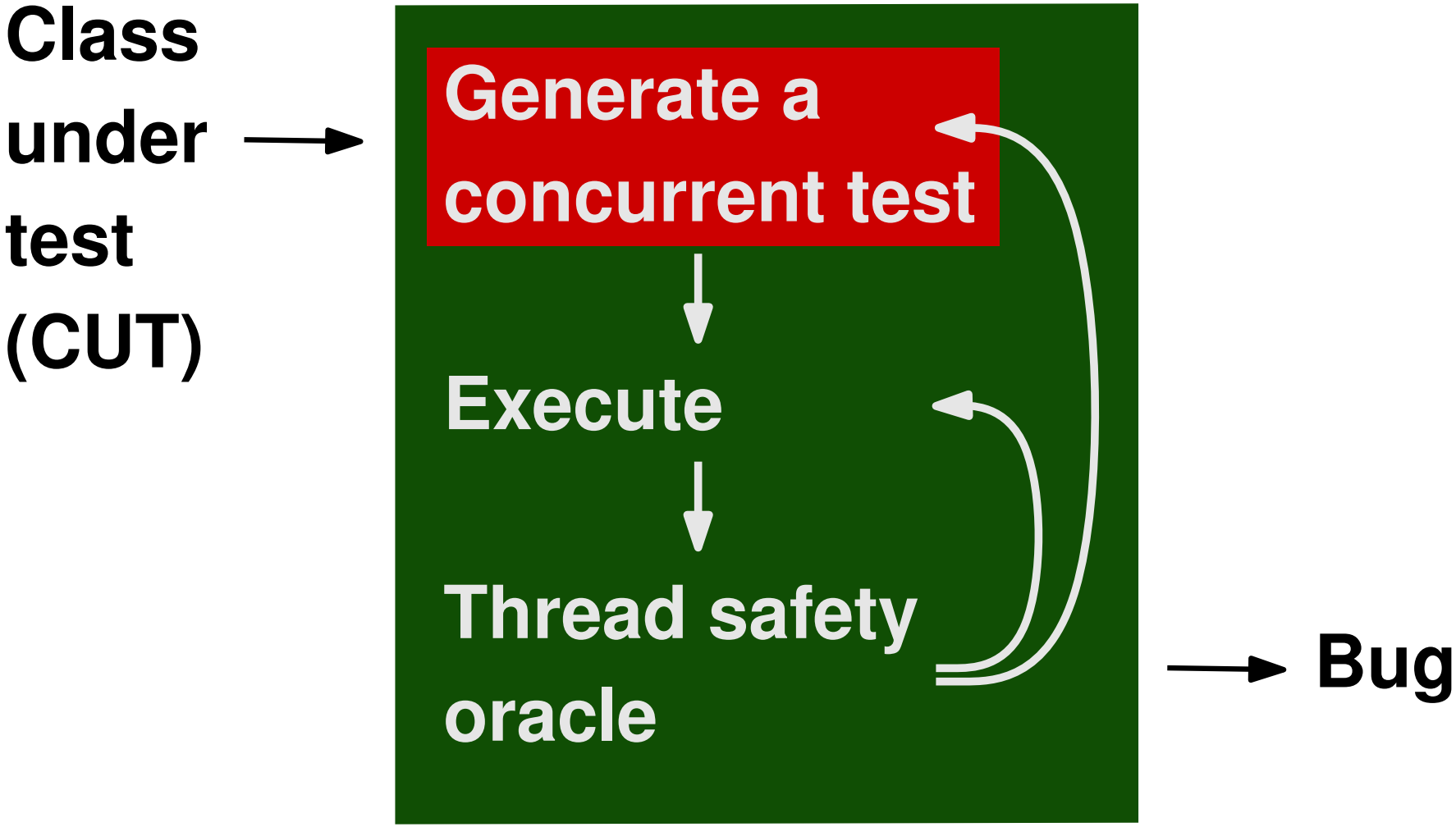
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Generate a concurrent test
Execute
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Bug

Generating Concurrent Tests

Example:

```
StringBuffer b = new StringBuffer()
b.append("abc")
```


```
b.insert(1, b)    b.deleteCharAt(1)
```

Generating Concurrent Tests

Sequential prefix:

Create and set up CUT instance

Example:

```
StringBuffer b = new StringBuffer()
b.append("abc")
```

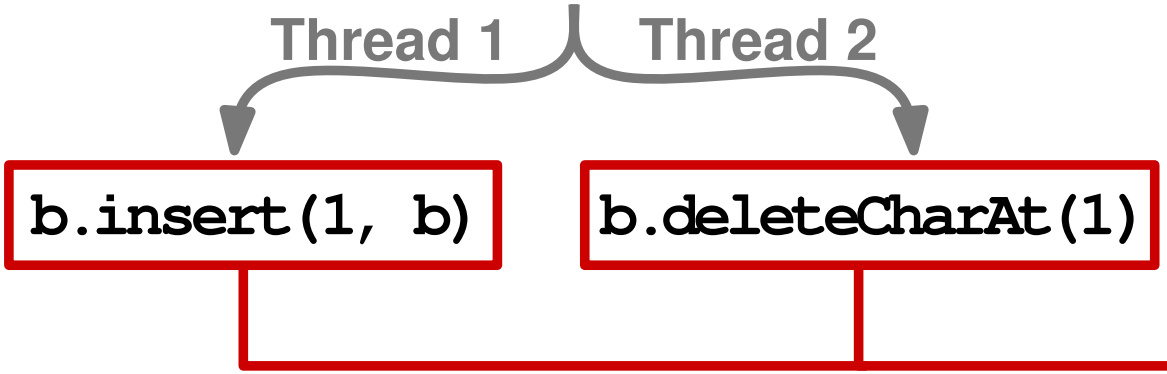
Thread 1 Thread 2

```
b.insert(1, b)    b.deleteCharAt(1)
```

Generating Concurrent Tests

Example:

```
StringBuffer b = new StringBuffer()
b.append("abc")
```



Concurrent suffixes: Use shared CUT instance

Test Generation Algorithm

1. **Create prefix**
   - Instantiate CUT
   - Call methods
2. **Create suffixes for prefix**
   - Call methods on shared CUT instance
3. **Prefix + two suffixes = test**

Selection of methods via feedback-directed test generation

Creating a Prefix

1. Create prefix

- Instantiate CUT
- Call methods

Creating a Prefix

1. **Create prefix**
   - Instantiate CUT
   - Call methods

Randomly select a constructor

Creating a Prefix

1. Create prefix

- Instantiate CUT
- Call methods

Randomly select a constructor

```
StringBuffer b = new StringBuffer()
```

Creating a Prefix

1. **Create prefix**
   - Instantiate CUT
   - Call methods

After adding a call: Execute

```
StringBuffer b = new StringBuffer()
```

Creating a Prefix

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Creating a Prefix

1. Create prefix

- Instantiate CUT
- Call methods

Randomly select a method

```
StringBuffer b = new StringBuffer()
```

Creating a Prefix

1. Create prefix

- Instantiate CUT
- Call methods

Randomly select a method

```
StringBuffer b = new StringBuffer()
b.append(/* String */)
```

Creating a Prefix

1. Create prefix

- Instantiate CUT
- Call methods

Arguments:

a) Take available object

b) Call method returning required type

c) Random value

```
StringBuffer b = new StringBuffer()
b.append(/* String */)
```

Creating a Prefix

1. Create prefix

- Instantiate CUT
- Call methods

Arguments:

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```
StringBuffer b = new StringBuffer()
b.append("abc")
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Creating a Prefix

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```
StringBuffer b = new StringBuffer()
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Creating Suffixes

2. Create suffixes for prefix

- Call methods on shared CUT instance

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StringBuffer b = new StringBuffer()
b.append("abc")
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Creating Suffixes

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- Call methods on shared CUT instance

Randomly select a method

```
StringBuffer b = new StringBuffer()
b.append("abc")
```

Creating Suffixes

2. Create suffixes for prefix

- Call methods on shared CUT instance

Randomly select a method

```
StringBuffer b = new StringBuffer()
b.append("abc")
```

```
b.insert(/* int */, /* CharSequence */)
```

Creating Suffixes

2. Create suffixes for prefix

- Call methods on shared CUT instance

Arguments:

a) Take available object

b) Call method returning required type

c) Random value

```
StringBuffer b = new StringBuffer()
b.append("abc")



b.insert(/* int */, /* CharSequence */)
```

Creating Suffixes

2. Create suffixes for prefix

- Call methods on shared CUT instance

Arguments:

a) Take available object

b) Call method returning required type

c) Random value

```
StringBuffer b = new StringBuffer()
b.append("abc")



b.insert(-5, b)
```

Creating Suffixes

2. Create suffixes for prefix

- Call methods on shared CUT instance

After adding a call: Execute

```
StringBuffer b = new StringBuffer()
b.append("abc")



b.insert(-5, b)
```

Creating Suffixes

2. Create suffixes for prefix

- Call methods on shared CUT instance

After adding a call: Execute

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StringBuffer b = new StringBuffer()
b.append("abc")



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Arguments:

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```
StringBuffer b = new StringBuffer()
b.append("abc")



b.insert(/* int */, /* CharSequence */)
```

Creating Suffixes

2. Create suffixes for prefix

- Call methods on shared CUT instance

Arguments:

a) Take available object

b) Call method returning required type

c) Random value

```
StringBuffer b = new StringBuffer()
b.append("abc")



b.insert(1, b)
```

Creating Suffixes

2. Create suffixes for prefix

- Call methods on shared CUT instance

After adding a call: Execute

```
StringBuffer b = new StringBuffer()
b.append("abc")



b.insert(1, b)
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Creating Suffixes

2. Create suffixes for prefix

- Call methods on shared CUT instance

After adding a call: Execute

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Creating a Test

3. **Prefix + two suffixes = test**

Creating a Test

3. Prefix + two suffixes = test

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```

Creating a Test

3. Prefix + two suffixes = test

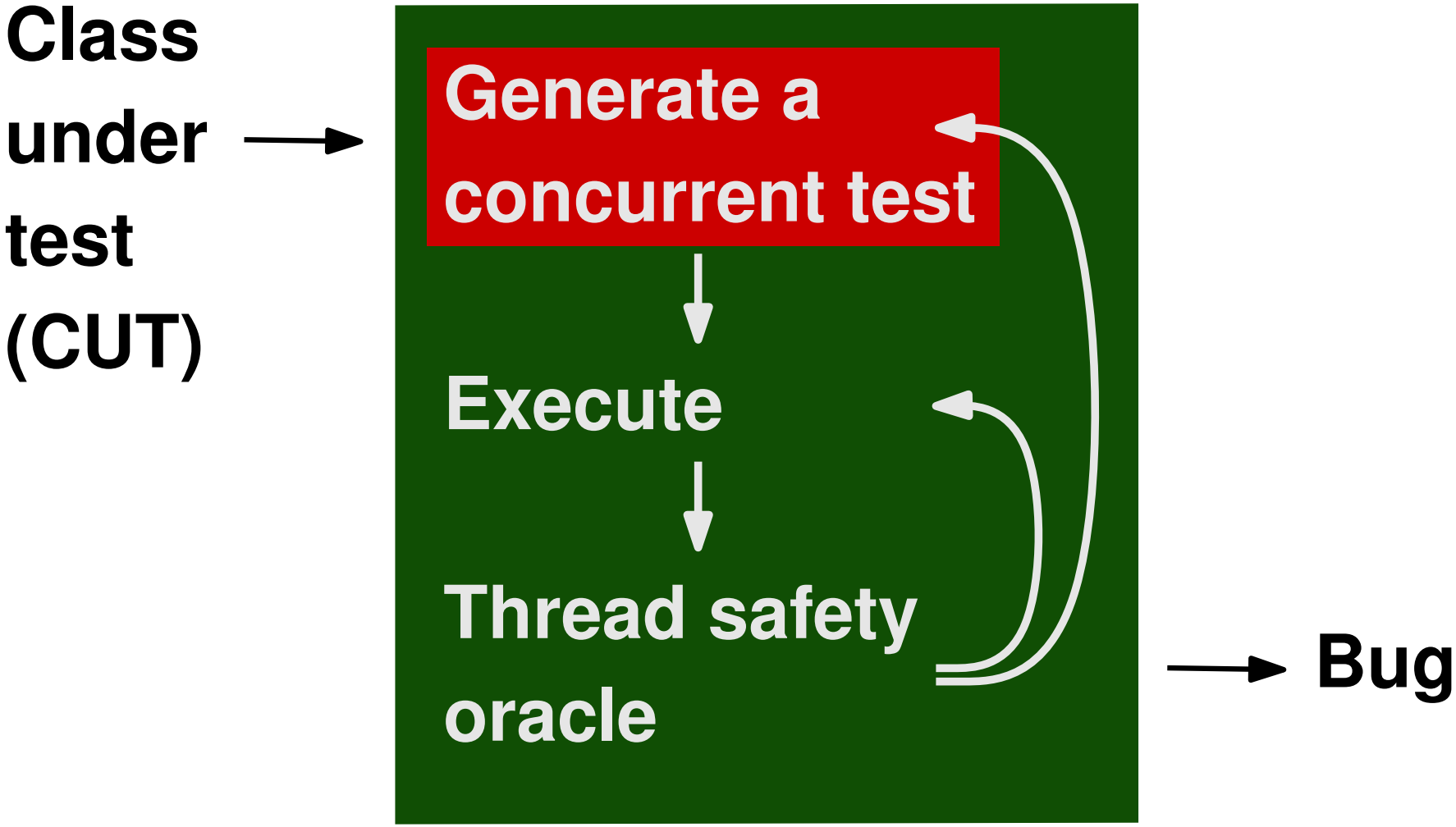
Spawn new thread for each suffix

```
StringBuffer b = new StringBuffer()
b.append("abc")
```

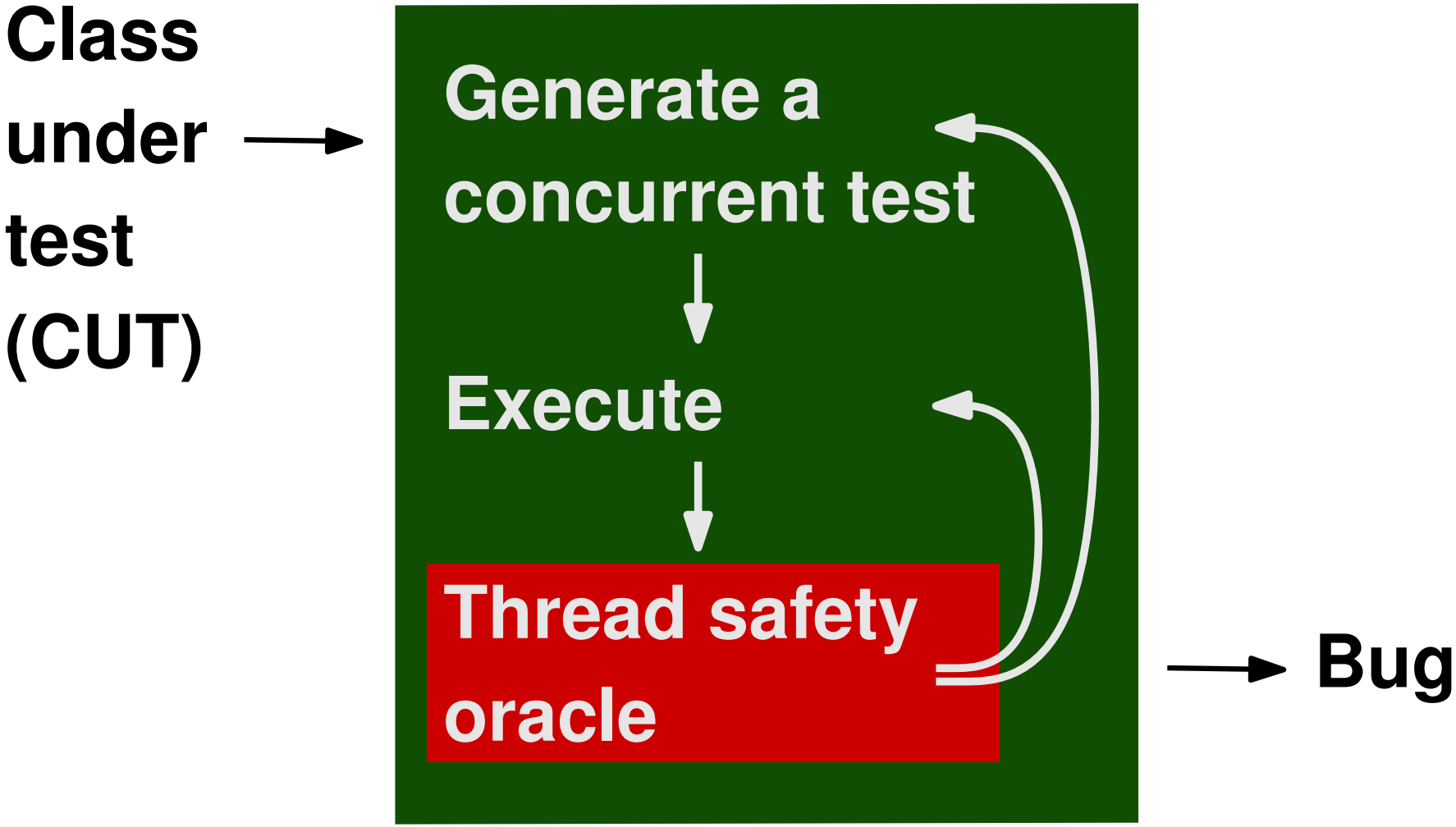
Thread 1 Thread 2

```
b.insert(1, b)    b.deleteCharAt(1)
```

Approach


Class under test (CUT)
Generate a concurrent test
Execute
Thread safety oracle
Bug

Approach


Class under test (CUT)
Generate a concurrent test
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Thread safety oracle
Bug

Thread Safety Oracle

Does the test execution expose a thread safety violation?

- Focus on exceptions and deadlocks
- Compare concurrent execution to linearizations

Linearizations

- **Put all calls into one thread**
- **Preserve order of calls within a thread**

Linearizations

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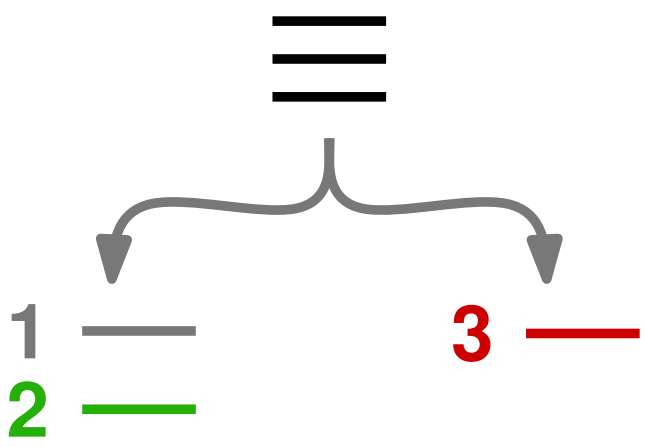
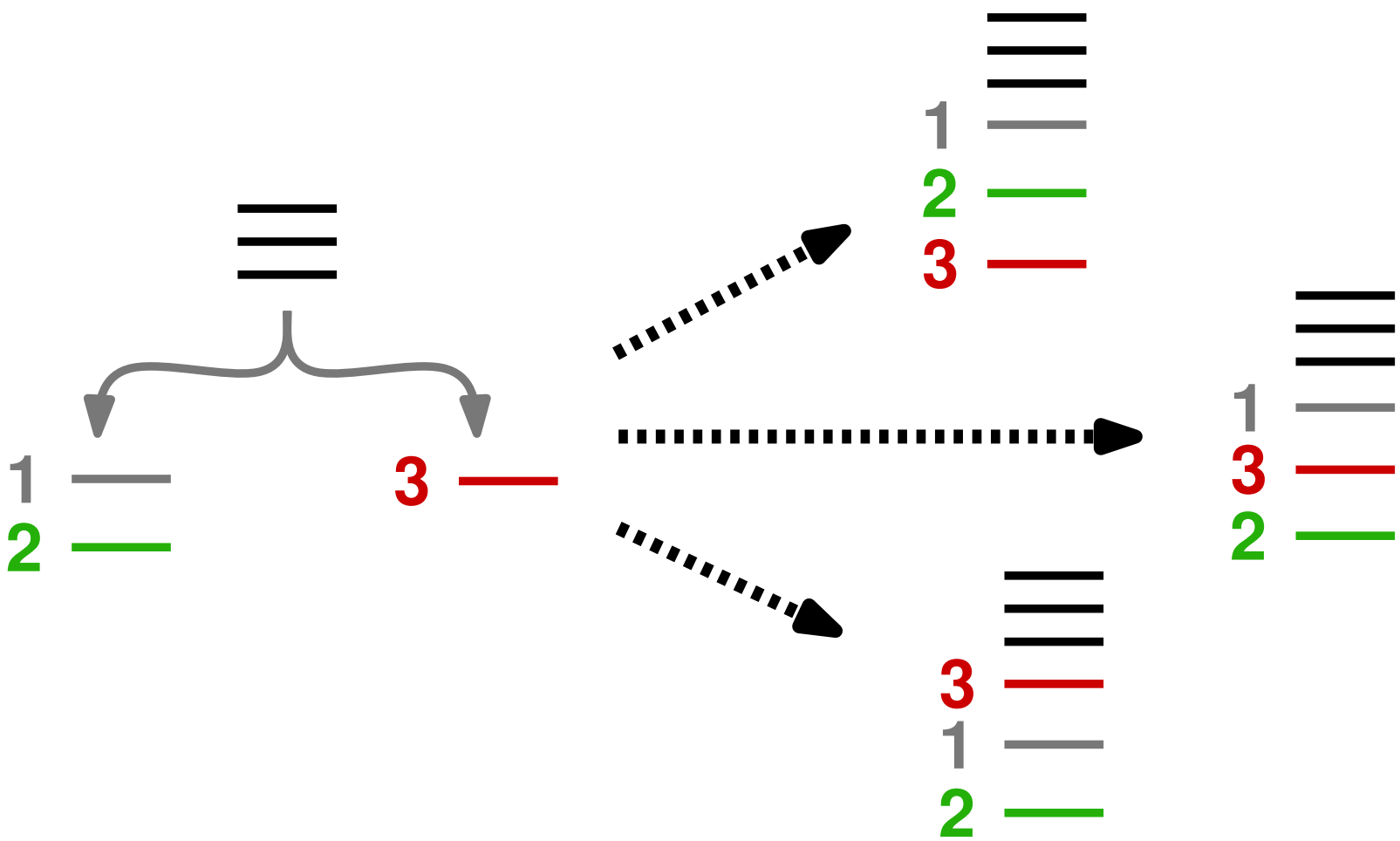
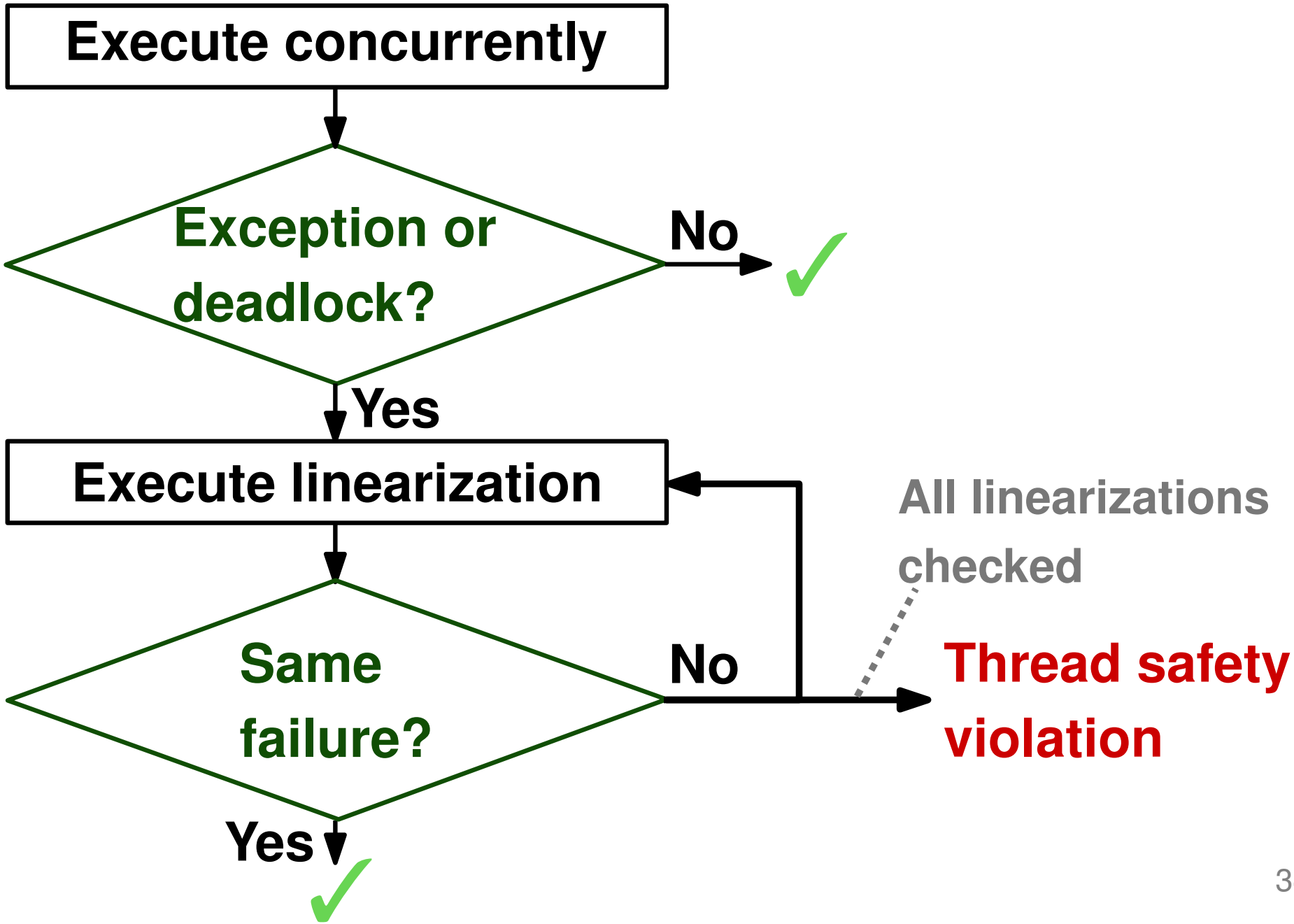


Linearizations

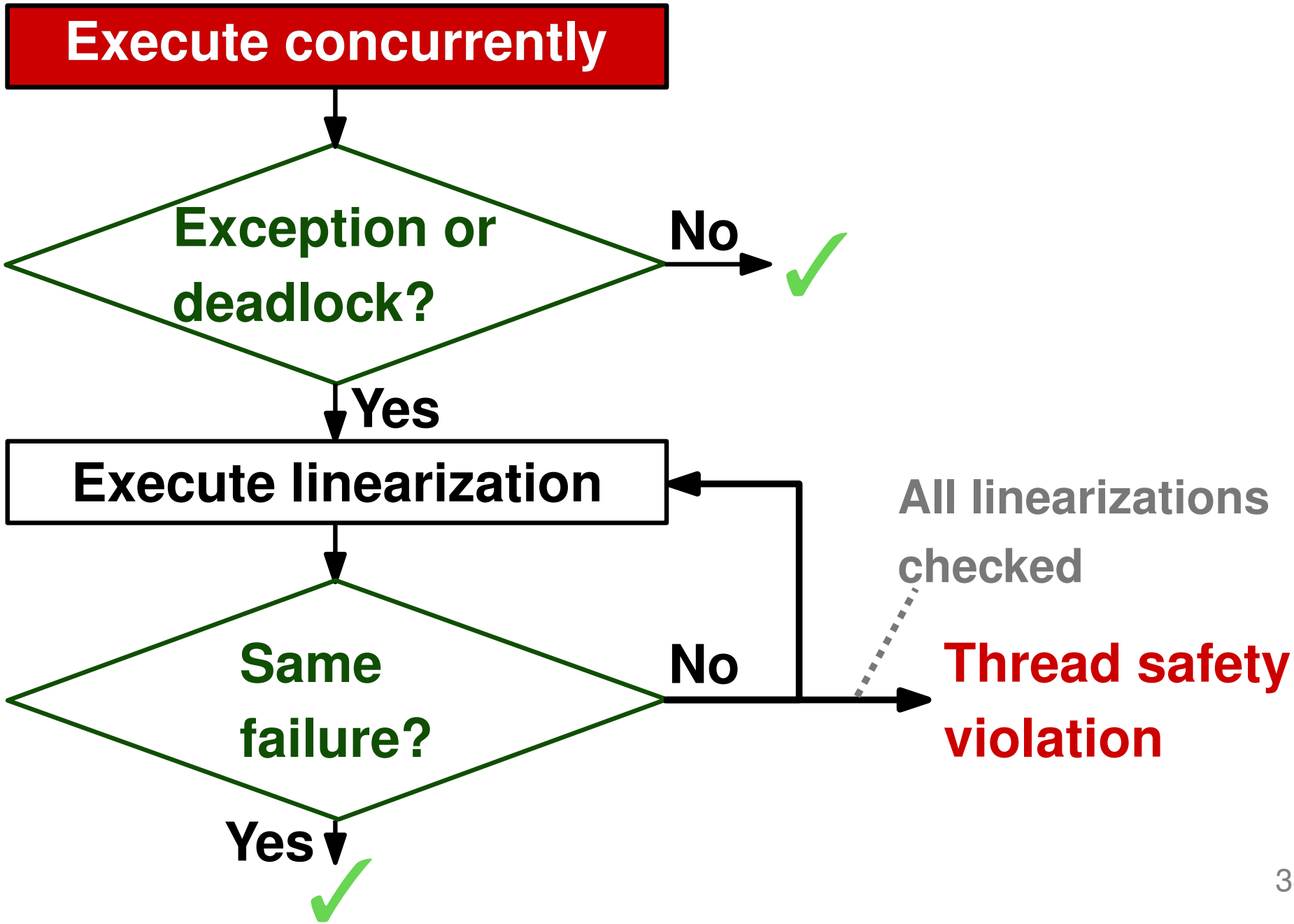
- **Put all calls into one thread**
- **Preserve order of calls within a thread**



The Oracle


Execute concurrently
Exception or deadlock?
No
Yes
Execute linearization
Same failure?
No
Yes
All linearizations checked
Thread safety violation

The Oracle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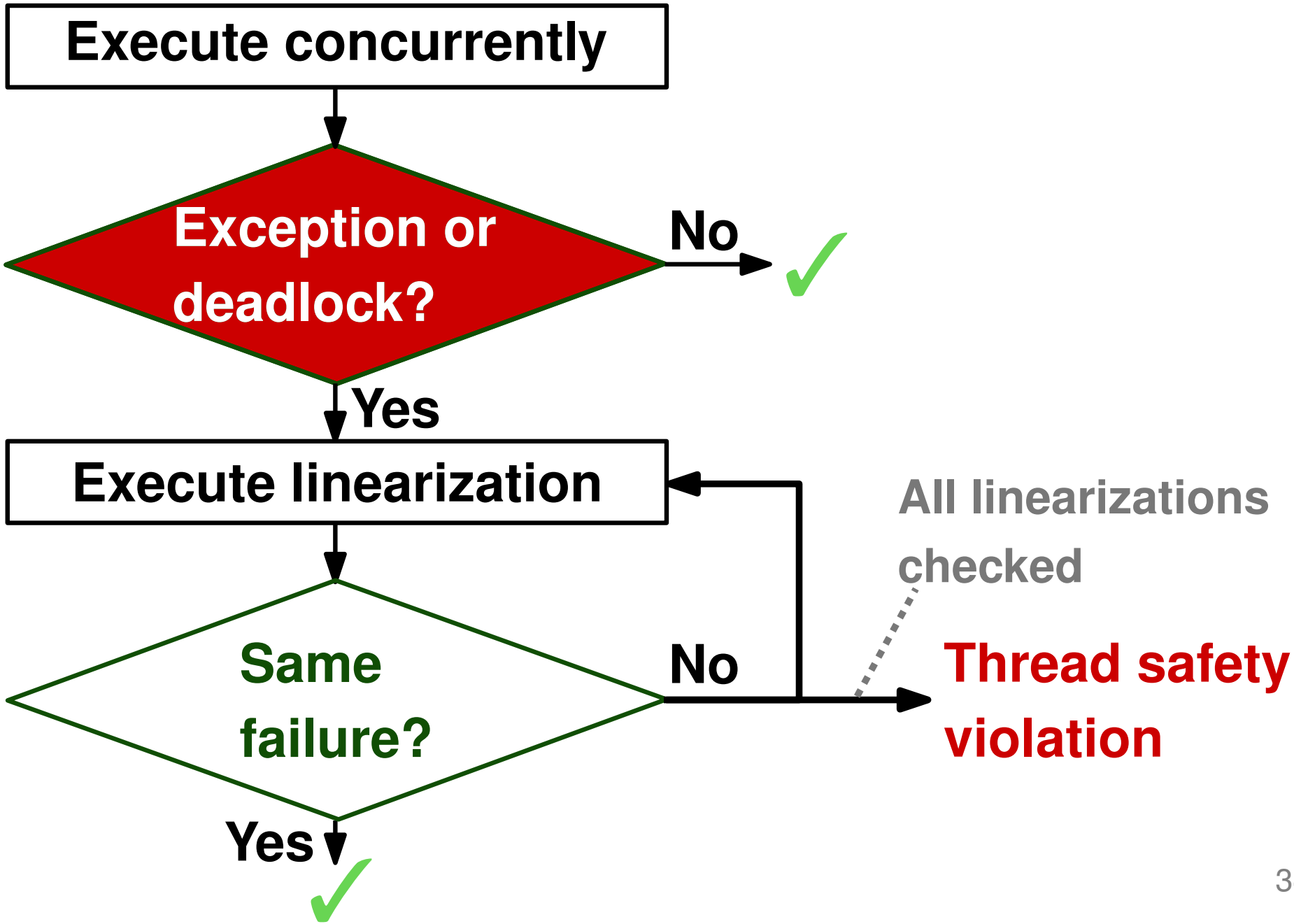
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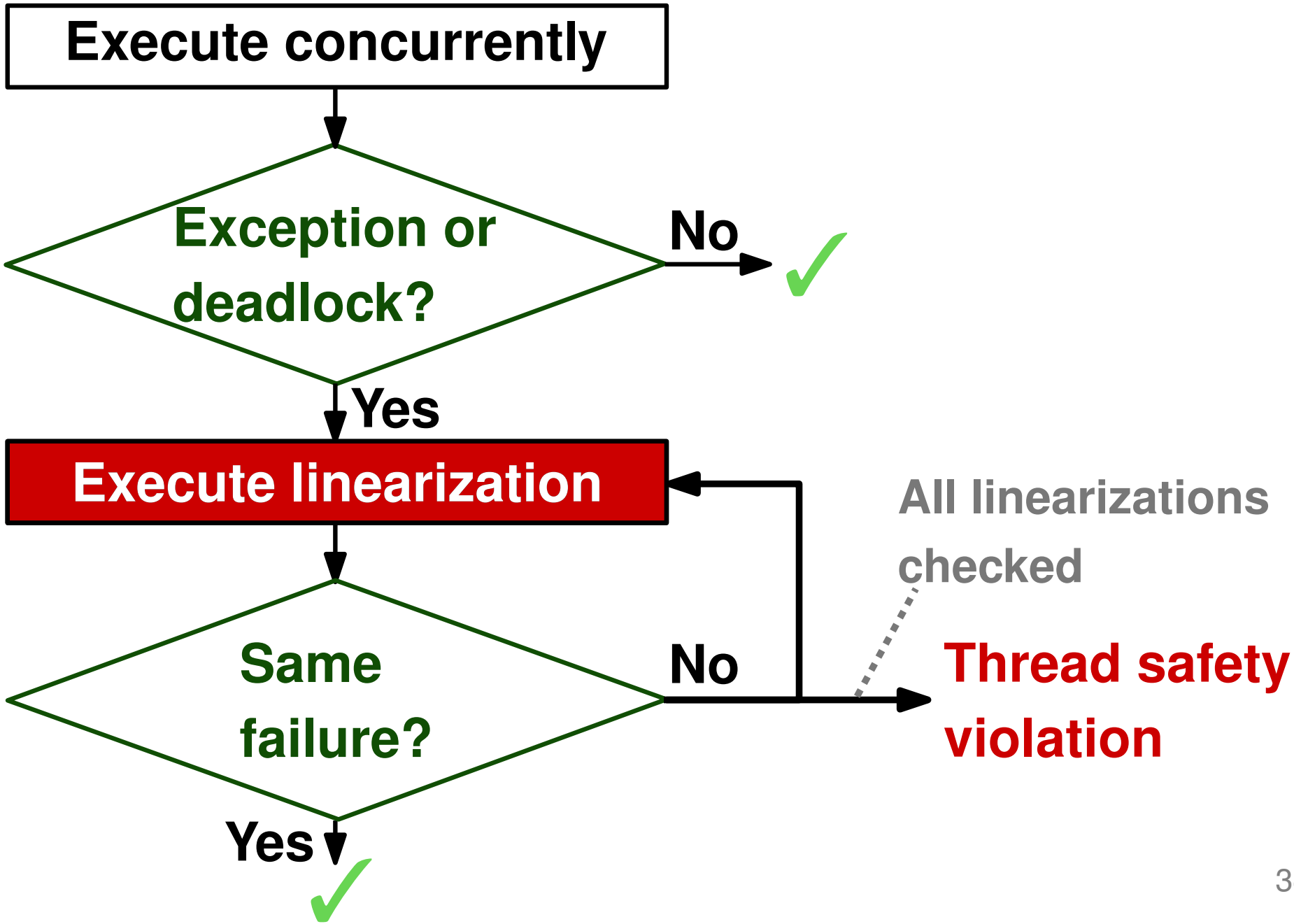
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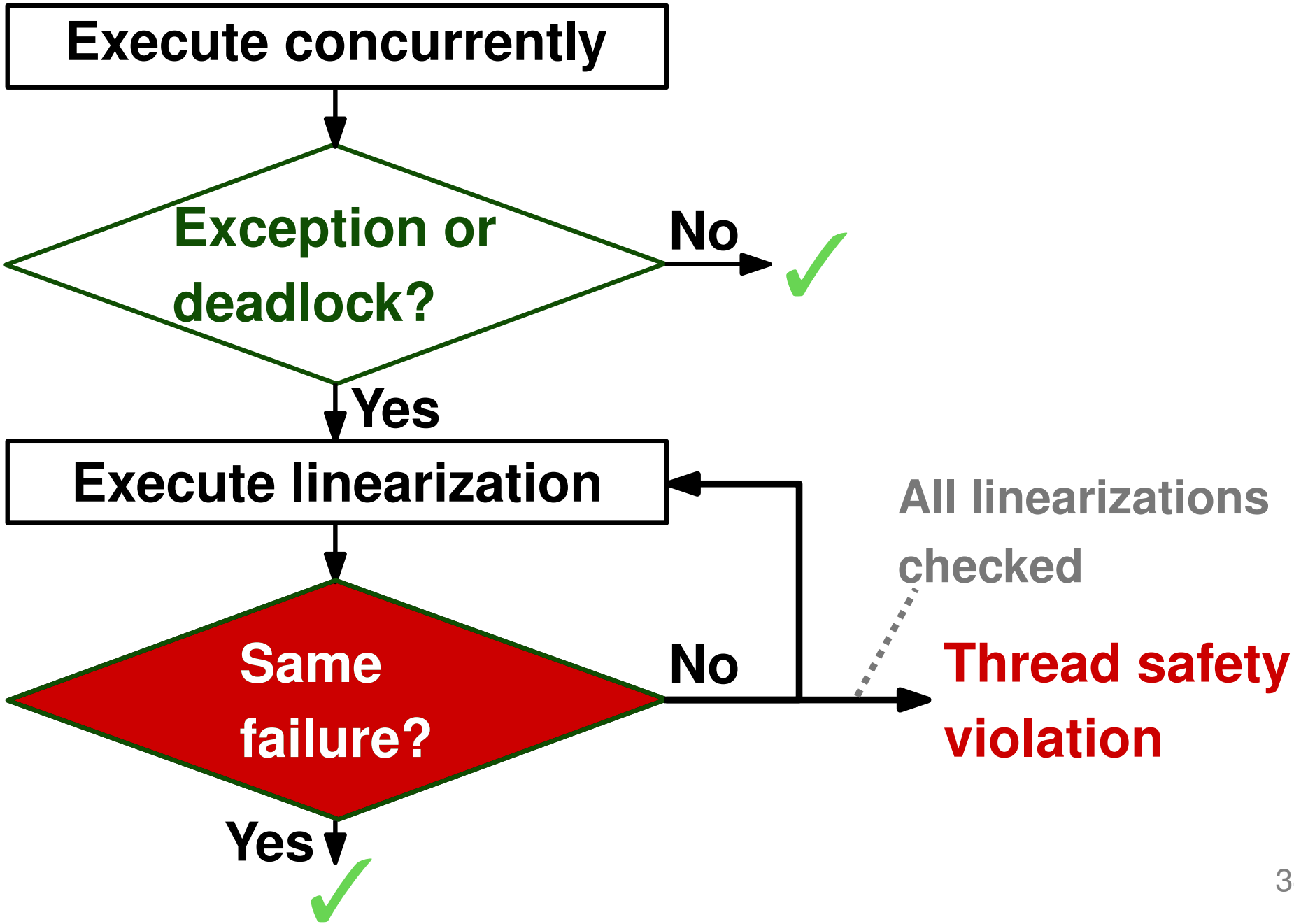
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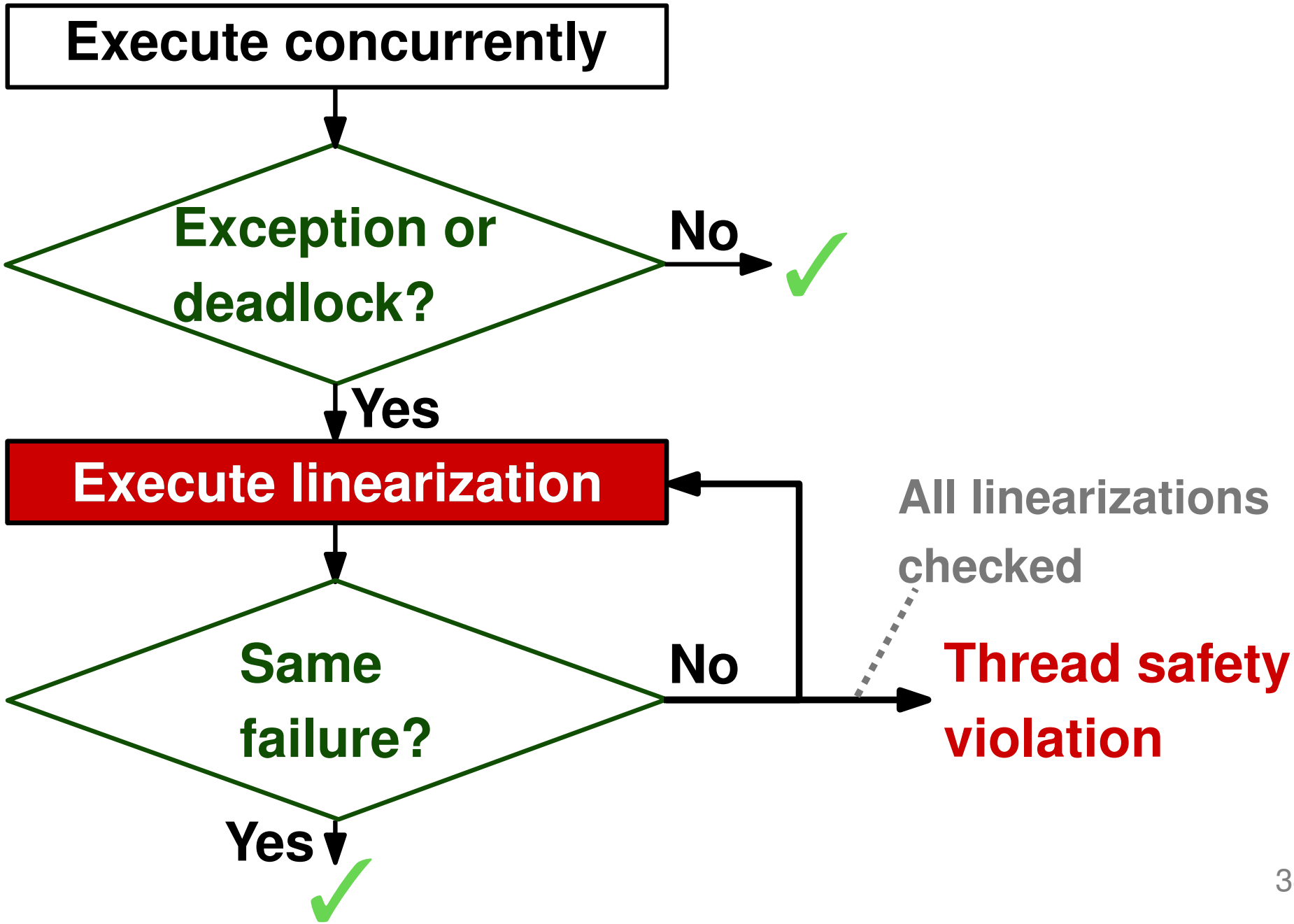
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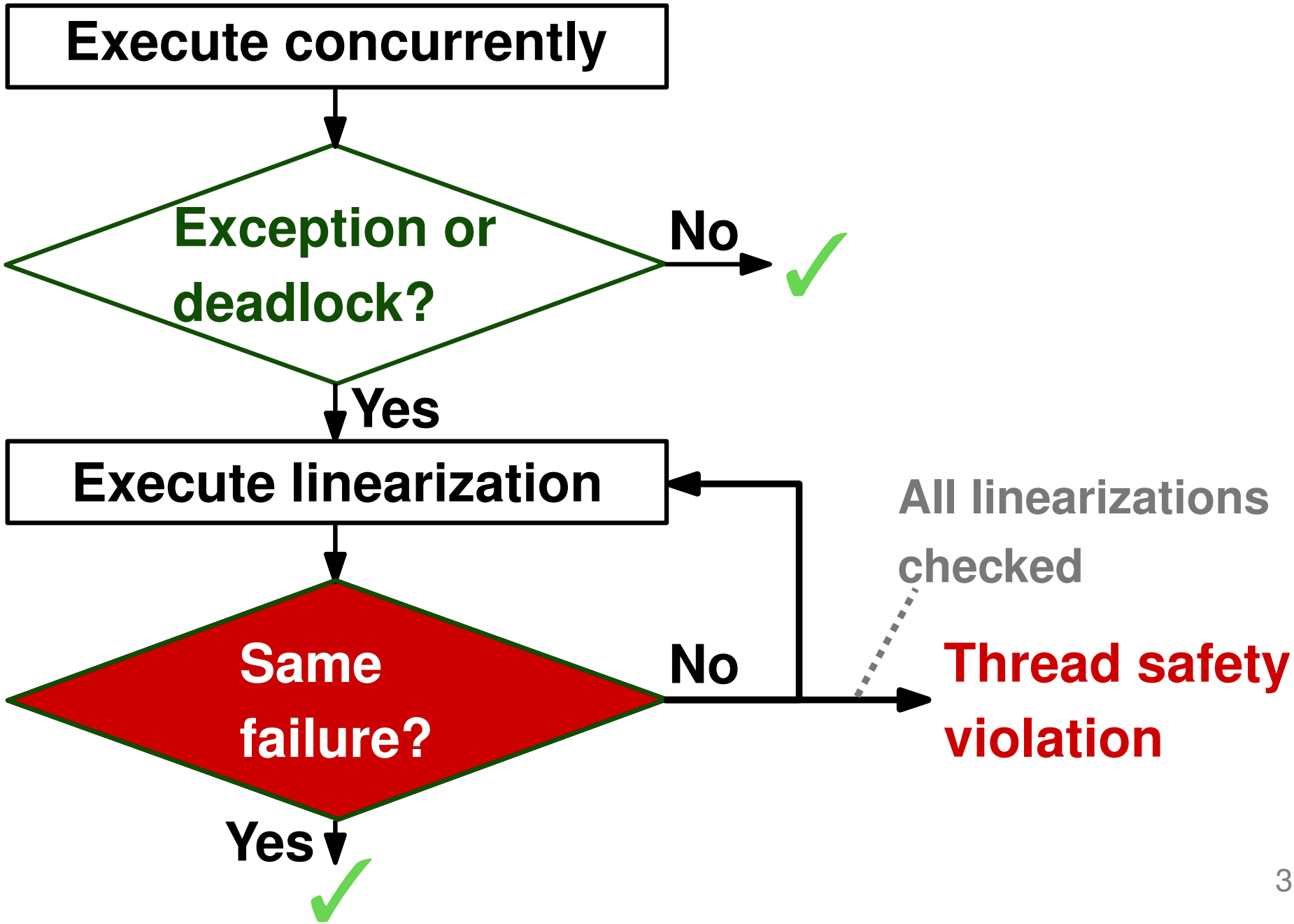
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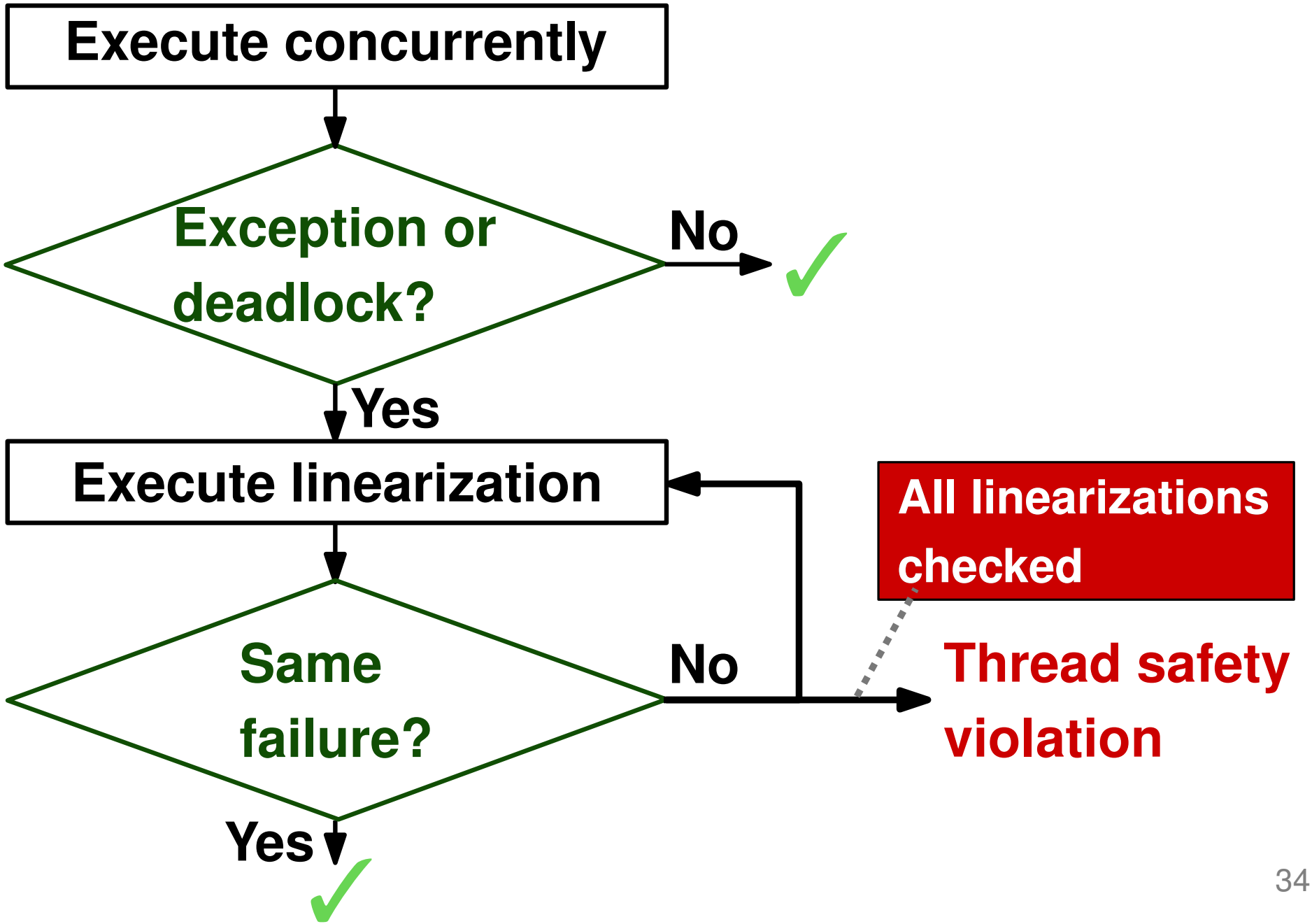
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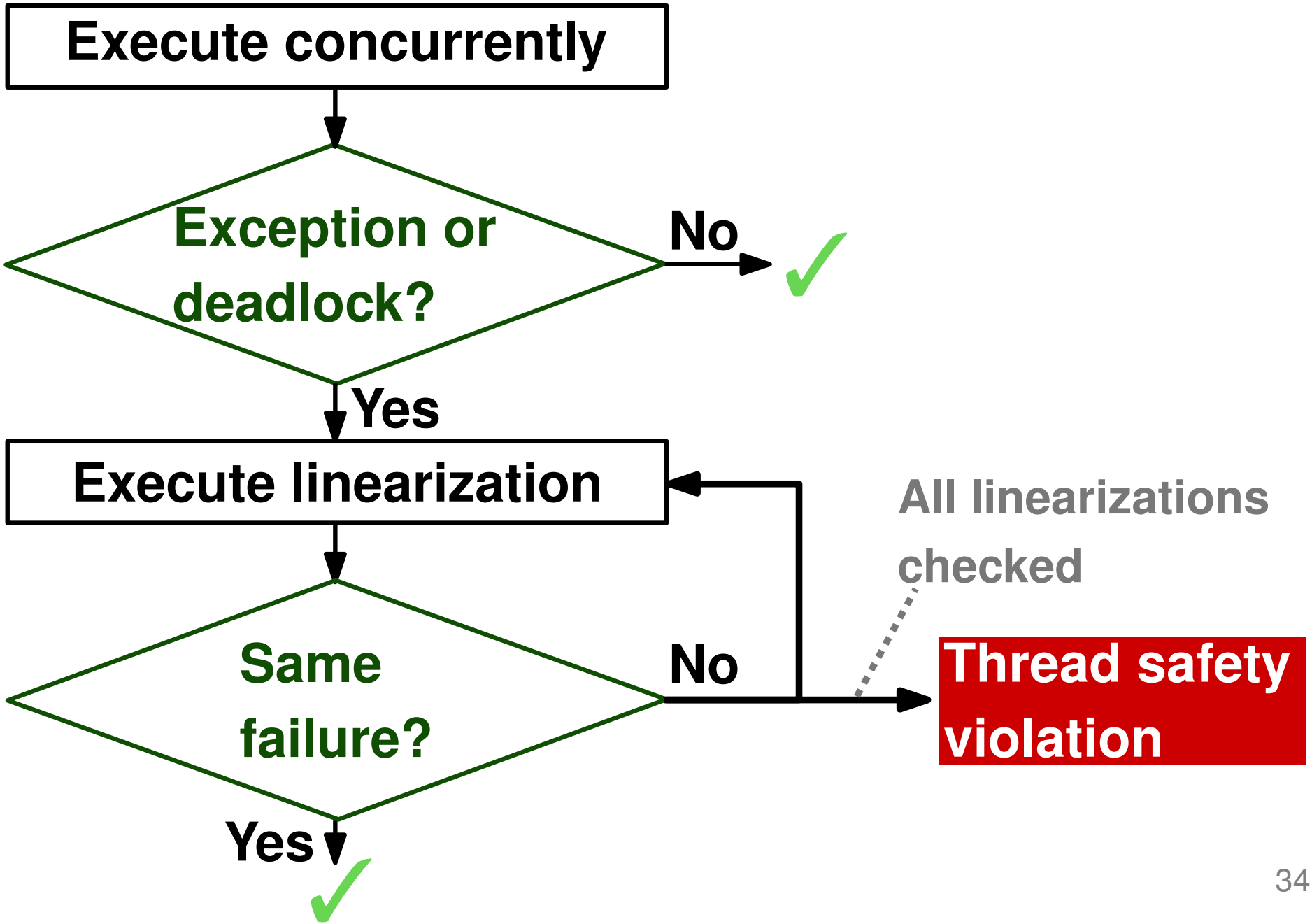
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Example

```
StringBuffer b = new StringBuffer()
b.append("abc")
```


```
b.insert(1, b)    b.deleteCharAt(1)
```

Example

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StringBuffer b = new StringBuffer()
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Thread 1 Thread 2

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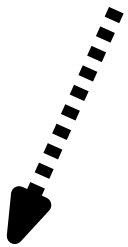

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b.append("abc")
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Example

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Thread 1 | Thread 2

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b.insert(1, b)      b.deleteCharAt(1)
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```
StringBuffer b = ..
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b.insert(1, b)
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Example

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Thread 1 Thread 2

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Thread safety violation

```
StringBuffer b = ..
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b.insert(1, b)
b.deleteCharAt(1)
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```
StringBuffer b = ..
b.append("abc")
b.deleteCharAt(1)
b.insert(1, b)
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Properties of the Oracle

Sound but incomplete *

- All reported violations are real
- Cannot guarantee thread safety

Independent of bug type

- Data races
- Atomicity violations
- Deadlocks

* with respect to incorrectness

Implementation & Results

- **Implemented for Java classes**
- **Applied to popular thread-safe classes from JDK, Apache libraries, etc.**
- **Found 15 concurrency bugs, including previously unknown problems in JDK**
- **Takes between several seconds and several hours (worst-case: 19 hours)**
  - Recent master thesis, published at ICSE'17: Worst-case time reduced to several minutes

Summary

- **Concurrent programming is inevitable**
- **Writing correct concurrent programs is hard**
- **Techniques to detect concurrency bugs**
  - Dynamic data race detection
  - Test generation and thread safety checking